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Research Paper

Wear characteristics of WSU total ankle replacement devices under shear and torsion loads

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ABSTRACT

Background: There are several factors that contribute to the failure of total ankle replacement (TAR). Aseptic loosening is one of the primary mechanisms of failure in TAR. Since a cross-linked ultrahigh molecular weight polyethylene (UHMWPE) is used as liner material, there is a need to quantify and develop methods to estimate the wear rates of the liners. High contact stresses develop during the gait generates wear debris resulting in osteolysis and early loosening of the prostheses.
Methods: In this paper wear characteristics of Wright State University (WSU) TARs were determined by applying shear and torsion loads. Viscoelastic properties were used to model the liner component. Finite element analysis was conducted to determine the wear rate by deriving Von Mises and contact stresses generated in the liner and wear rate equation was used to predict the wear rate.
Results: Titanium alloy has shown less resistance towards shear forces when compared with other metal alloys. Under torsion, rotation angle plays a significant role in affecting the peak stress values. The maximum average contact stress was 14.46 MPa under torsion load which contributes to a wear rate of 0.67 (mm^3/year) for one of the mobile bearing models. The maximum average contact stress and wear rate obtained from the analytical study were 10.55 MPa and 0.33 (mm^3/year), respectively for mobile bearing models. When compared with mobile bearing model, fixed bearing model has shown higher stresses at different degrees of rotation.
Conclusion: Both shear and torsion loads cause significantly lower contact stresses and wear when compared to the axial load. Further studies are necessary to accurately determine the wear behavior of fixed bearing TAR models.

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1. Introduction

Total ankle replacement (TAR) is emerging as an alternative to ankle arthrodesis and treatment option for patients suffering from ankle arthritis. The advantage of replacing the ankle joint helps in preserving the movement and function of the joint (Gougoulias et al., 2009). This results in relief from pain and also improves gait by reducing limp and protection of other joints (Valderrabano et al., 2003a). Though the short term and intermediate outcomes were satisfactory, long term follow up studies have shown higher failure rates due to major complications like infections and loosening of the components (Michael et al., 2008; Gougoulias et al., 2009). Even though major improvements were made to TARs in the past two decades, revision rates in TARs continue to be higher when compared with hip and knee arthroplasty (Jay Elliot et al., 2014). A mean rate of 3.29 revisions per 100 patients was reported in case of total ankle replacement which is significantly higher when compared to revision rate of 1.29 and 1.26 in case of total hip and knee replacements respectively (Labek et al., 2011). Aseptic loosening of the prostheses was reported as a major cause of revision in Swedish and Norwegian TAR registries (Henricson et al., 2007; Fevang et al., 2007). The rates of major revision surgery after total ankle replacement are high when compared to arthrodesis where a revision rate of 9% for one year and 23% for five years was observed for a total of 480 ankle replacements (SooHoo et al., 2007).

Major factors that contribute to failure of total ankle replacements are fixation method and component design (Nishikawa et al., 2004). Because of its superior mechanical properties like high strength, low creep, low friction coefficient and good resistance to fatigue, UHMWPE is used as a liner material in TARs since 1960s (Li and Burstein, 1994; Lewis, 1997; Affatato et al., 2009). Similar to hip and knee, the articulation between a metal and UHMWPE generates wear and the polymer debris result in osteolysis (Gupta et al., 2010). The surface area of the ankle is much smaller, one-third, compared to that of hip or knee joints (Michael et al., 2008). More than 75% of the load acts on superior articular surface of the talus and peak stresses are observed in the anterior and lateral regions of the talar dome (Kimizuka et al., 1980). The primary source of loading on the ankle occurs during walking, especially during the stance phase of the gait cycle. During weight-bearing conditions nearly 77–90% of the load is transferred to the dome of the talus (Michael et al., 2008). Ankle joint experiences a load of five to seven times the weight of human body during the stance phase of the gait cycle (Stauffer et al., 1977). The small surface area of the talar bone and higher joint reaction forces generate very high contact stresses in TARs (Jay Elliot et al., 2014). Due to cyclic contact stresses at articular surfaces (i.e. between the liner and metal components) in TARs, UHMWPE undergoes pitting, delamination and changes in the crystal structure, resulting in low resistance to wear (Edidin et al., 1999; Taddei et al., 2008; Wannomae et al., 2006). Wear particles generated from the liner causes osteolysis in the periprosthetic tissues resulting in early loosening of the implant (Lewis, 1997).

Excessive shear forces at the bone–implant interface can be observed in case of incorrect bony cuts and this condition further increases the chance of talar subsidence which is also the most common cause for aseptic loosening of the implant (Gupta et al., 2010). Tochigi et al. (2006) observed changes in the contact stresses at different locations of the ankle joint when subjected to shear forces and rotation torques. During vertical loading conditions, both bone–implant interface and TAR components are under compression. Unlike vertical load, rotational forces, antero-posterior, and medial–lateral shear forces do not contribute to implant stability but lead to implant loosening and polyethylene wear (Haskell, 2012). Current TAR devices are available either with mobile bearing (three component) or with fixed bearing (two component). When compared with mobile bearing, fixed bearing design shows greater stability with less risk of bearing dislocation (Gaudot et al., 2014). Unlike fixed bearing devices, mobile bearing devices are less susceptible to tibial component loosening due to lower shear forces at bone–implant interface (Gaudot et al., 2014). Several biomechanical studies conducted on these devices showed that three component designs have better performance in terms of biomechanics and kinematics when compared with two component designs, but no significant difference was found between these devices clinically in terms of ankle motion (Valderrabano et al., 2003a, 2003b, 2003c, 2012; Gaudot et al., 2014). However, there is a debate regarding the advantages and disadvantages of each type. For successful ankle prosthesis, the implant should withstand shear forces acting on the ankle joint at the same time provide wear resistance during different loading conditions.

Kinematics of the replaced joint and contact pressures generated at prosthetic articulating surfaces play a major role in TAR success (Reggiani et al., 2006). There is a lack of knowledge on the kinematics and contact pressures, and computational modeling using finite element analysis on TAR devices. Most of the studies in the literature discuss axial normal loads (Anderson et al., 2006; Jay Elliot et al., 2014) and their effects in stress development and wear. The main objective of the present study is to understand the role of contact stresses affecting the wear characteristics of TARs under shear and torsion loads. For this study, second generation WSU TAR models were analyzed. The contact stresses obtained during shear and torsion loads in this study were used to determine the yearly wear rate of the TARs under those load cases. Contact stresses and wear rate values obtained in this study were then compared with values obtained under axial loading conditions from a previous effort (Jay Elliot et al., 2014).

2. Materials and methods

Finite element analysis was performed using ABAQUS to determine the wear rate in WSU TAR models. Second generation TAR models were considered for this study and the solid models of respective TARs are shown in Fig. 1. Traditionally all the models are three component prostheses with mobile bearing. Tibial, bearing/liner and